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Problems Associated with Plate Bonding Methods of Strengthening Reinforced Concrete Beams

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Abstract: This paper reviews works on problems associated with plate bonding or plating methods of strengthening reinforced concrete beams. Every structural element should be designed for a particular type of loading. However many civil structural elements, like reinforced concrete beams are often required to be upgraded or strengthened due to increased load requirements. Strengthening is becoming both environmentally and economically more preferable than replacement. Different types of materials and methods such as sprayed concrete, ferrocement, steel plate and fibre reinforced polymer (FRP) are available for strengthening existing reinforced concrete beams. However, plating methods of steel plate and FRP laminate are the most popular methods amongst the other methods. In this paper, strengthening of plating methods by using steel plate and fibre reinforced polymer (FRP), and the methods of applying these materials are reported. The advantages and disadvantages of these materials are also reported. Furthermore the problems associated with this plating methods by using two these two materials (steel and FRP) are briefly discussed in this paper.

Key words: Reinforced concrete beam, strengthening, steel plate, fibre reinforced polymer, debonding.

INTRODUCTION

A large number of civil infrastructures around the world are in a state of serious deterioration today due to carbonation, chloride attack, etc. Moreover many civil structures are no longer considered safe due to increase load specifications in the design codes or due to overloading or due to underdesign of existing structures or due to lack of quality control. In order to maintain efficient serviceability, older structures must be repaired or strengthened so that they meet the same requirements demanded of structures built today and in future. It is becoming both environmentally and economically preferable to repair or strengthen the structures rather than replacement, particularly if rapid, effective and simple strengthening methods are available. This paper describes the plating method of strengthening using steel plate and FRP laminate and their advantages and disadvantages. This paper also highlights the common problems of this plating method.

Objectives: The main objectives of this paper can be summarized as follows,

- Review the existing strengthening methods.
- Highlights the plate bonding methods of strengthening using steel plate and FRP laminate.
- Highlights the problems associated with these plate bonding methods.

Literature review: Strengthening of reinforced concrete beam is a common task of concrete structures maintenance nowadays. For the purpose of strengthening, several materials and methods are available such as sprayed concrete, ferrocement, steel plate and fibre reinforced polymer (FRP). Sprayed concrete is the oldest materials amongst the group and is the most common method of repairing and strengthening of reinforced concrete structures. Sprayed concrete has been used in strengthening concrete for almost 90 years. The technique of strengthening of reinforced concrete beam by using sprayed concrete as reported by Diab[2]. It is nothing but the addition of steel reinforcement bars covered with a layer of sprayed concrete or sprayed fibre concrete to enhance its behaviour, to overcome damage to the effected element, or to strengthen the element after an excessive overloading condition. Ferrocement is another material which is used for strengthening of reinforced concrete (r.c.) structures. It has the same cementitious material as reinforced concrete. Dinardo and Ballingall[3] have reported that the incorporation of fine wire mesh beneath the surface of repair mortar has long been practiced although these methods were not identified as ferrocement. The use of the term ferrocement in repair was first introduced by Romuldi and Irons[17,9] in the early 1980s. It was mainly used as relining membranes for the repair of liquid retaining structures, such as pools, sewer lines and tunnels. The use of ferrocement laminates as

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strengthening components for the repair of beams was investigated by Paramasivam *et al*.[16].

However, among all of the strengthening materials, steel plate and FRP laminate are the most common and effective materials due to their several advantages which will be described in the next section.

Plate bonding methods of strengthening r.c. beams

Strengthening using steel plate: Steel plate is one of the most common materials for strengthening of reinforced concrete beam. It is very effective for increasing the flexural and shear capacity of reinforced concrete beam. Strengthening by steel plate is a popular method due to its availability, cheapness, uniform materials properties (isotropic), easy to work, high ductility and high fatigue strength. Investigations into the performance of members strengthened by this technique were started in the 1960s. This method had been used to strengthen both buildings and bridges in countries such as Belgium, France, Japan, Poland, South Africa, Switzerland and United Kingdom[10]. More recently, research works on strengthening using steel plate were carried out in the United Kingdom at a number of centres, most notably at the Department of Civil and Structural Engineering of Sheffield University.

The most common form of plating is to glue steel plates to the tension faces of beams. In this position, the plate is at its furthest extremity from the compression region and, as a result, the composite flexural action is at its maximum[15]. Furthermore, the composite action between the plate, glue, and concrete will be maintained until failure[19]. However the effectiveness of this method is depended on the surface preparation and bonding methods between existing beam and steel plates. Thus, the surface preparation of existing beam as well as steel plate has to be carried out effectively. Adhikary *et al*.[1] has described the roughening process of the beam surface before placing the plates. The roughening process is carried out using a mechanical grinding until the laitance was removed and the surfaces were then brushed and cleaned thoroughly with acetone. The bonding faces of the steel plates can also be sand-blasted and then cleaned with acetone. After surface preparation epoxy adhesive is placed on the roughened surface and then steel plate is positioned on top. Various research works on the methods of plate bonding methods are outlined below.

The first research work done on steel plate bonding methods of strengthening reinforced concrete beam was conducted by Swamy *et al*.[19]. The main parameters investigated were plate thickness, glue thickness, layered plates, lapped plates, variation in glue thickness, and the presence of stress concentration in the adhesive layers. The results had shown that the addition of glued steel plates to reinforced concrete beams can substantially increase their flexural stiffness, reduce cracking and structural deformations at all load levels, and had contribute to a modest increase in their ultimate flexural capacity. The reduction in cracking and deformations had increased with increasing plate thickness and also with increasing glue thickness, although not at the same rate. They had also reported that the glued plates contributed more to the control of cracking than to the control of deflection. Both beam action and composite behaviour can be preserved until failure provided that appropriate glues are chosen and adequate precautions are observed in the gluing technique. The glued plates can increase the ultimate flexural capacity by 10 to 15%, and this can be satisfactorily predicted by current design procedures. Jones *et al*.[10] tested seven beams strengthened by steel plates. A number of techniques were investigated such as tapered plates, multi-plates with curtailment, and anchor bolts, all of which have been used successfully in other applications. Hussain *et al.*[8] had also used the steel plates for strengthening pre-cracked reinforced concrete beams by plate bonding method. They concluded that reinforced concrete beams preloaded to 85 percent of ultimate capacity can be repaired effectively by the plate bonding technique. The ductility of the repaired beams decreases as plate thickness increases.

Strengthening using fibre reinforced polymer (FRP): Fibre reinforced polymer (FRP) for civil engineering structures are being increasingly studied in recent years. These materials are being used in the aerospace, automotive and shipbuilding industries for almost two decades[7]. In general, FRP offer excellent resistance to corrosion, good fatigue resistance (with the possible exception of some glass-based FRP), low density, high stiffness and strength, and a very low coefficient of thermal expansion in the fibre orientation. Garden and Hollaway[4] have described FRP materials as having superior mechanical and physical properties than steel, particularly with respect to tensile and fatigue strengths. Furthermore these qualities are maintained over a wide range of temperatures. However, its higher price, relatively low failure strains, and unknown long-term performance have for many years restricted the use of FRP for civil engineering structures[13]. Until recently some FRP can cost as much as 10 times by weight of traditional structural materials, such as structural steel. Notwithstanding the lack of practical knowledge of FRP, this fact alone probably would have kept FRP from becoming commonly used in the construction industry. Despite declining prices in composites as a result of improved manufacturing processes, FRP still remains relatively expensive when compared to traditional materials. Thus, FRP is usually considered only for special applications, such as in non-magnetic structures, or for use in aggressive corrosive environments. However, the usage of FRP can be more economical than using steel plates. This is because the material costs in a rehabilitation project rarely exceed 20 percent of the total cost of the repair. The remaining 80 percent is spent primarily on labour and implementation costs. It is in this 80 percent that FRP can significantly reduce the cost of rehabilitation[11]. The application process for the FRP can be carried out from a light scaffolding or a mobile platform, often during a 24 hour period, as compared to several days required to apply heavy steel plates using complex scaffolding systems.

Several fibre reinforced polymer (FRP) systems are now commercially available for the external strengthening of concrete structures. Grace *et al*.[5] described the fibre materials commonly used in these systems which include glass, aramid, and carbon. The fibres are available in many forms such as pultruded plates, uniaxial fabrics, woven fabrics and sheets. Amongst the material available, carbon fibre reinforced polymer (CFRP) laminate is a popular choice of material due to its high strength. Although, FRP are more effective for flexural strengthening rather than shear strengthening due to its anisotropic properties, shear strengthening can be achieved if the fibre orientation is changed. For strengthening r.c. beams, the FRP application techniques on soffit of the beam are similar to steel plate application.

FRP composite materials were first introduced in the early 1940s. In 1986, the world's first highway bridge using FRP reinforcing tendons was built in Germany[6]. The first FRP pedestrian bridge was erected in 1992 in Aberfeldy, Scotland. In the U.S., the first FRP concrete bridge deck was built in 1996 at McKinleyville[6]. The Ibach Bridge located at Lucerne, Switzerland was first bridge to be repaired using CFRP[11]. A total of 6.2 kg of CFRP was applied to the bridge instead of 175 kg of steel plates, had a steel plating process been used instead. The first step toward the development of FRP for the rehabilitation of reinforced concrete structures was to determine the benefits and limitations. Research projects into the use of FRP as a means of rehabilitating flexural members demonstrated consistently positive results. These investigations determined that the external FRP sheets behave as conventional reinforcement. The sheets increased flexural strength by introducing a second couple between the sheet and the compressive stresses in the concrete.

The work carried out by Saadatmanesh and Ehsani[18] at the University of Arizona had dealt predominantly with the rehabilitation of reinforced concrete beams using glass FRP (GFRP) sheets. Their results showed that an increase in the cross-sectional area of the sheet applied and the epoxy thickness used to apply it would result in an increase in flexural strength. Their experimental data agreed closely with theoretical results using beam theory.

Meier and Kaiser[12] first reported on the application of carbon fibre reinforced polymer (CFRP) as a rehabilitative method. Significant improvement in the flexural capacity of the beams was found which reflects on the results of the GFRP strengthened beam by Saadatmanesh and Ehsani[18]. Due to high stiffness added to the member by the carbon fibre sheet, deflections in the beams were considerably less than those in the control beams. In adition, the size and distribution of cracks in the beams were significantly altered. The crack widths were much smaller, with the cracks being more evenly distributed throughout the length of the beam.

Problems associated with plate bonding methods of strengthening: Adhesively bonding a plate to a RC beam produces a plated beam with full interaction and, hence, the composite plated beam can be analyzed or designed using all the conventional procedures that are available for RC structure. However, adhesively bonded plates are highly susceptible to premature debonding. Extending the tension face plate past the point of contraflexure in a continuous beam so that the plate terminates on a compression face will not prevent debonding.

The problem of preventing premature debonding of adhesively bonded plates is an extremely complicated problem. It is also an extremely important problem because invariably debonding of adhesive joints is a brittle and catastrophic failure mechanism. Oehlers[14] mentioned, research has shown that there are three mechanisms of debonding which will be referred to as:

- Flexural peeling
- Shear peeling
- Axial peeling

The problem is further compounded by the fact that these three mechanisms of premature debonding interact. A solution has been found by first deriving a mechanism of failure for each debonding mechanism separately and then their interaction.

Flexural peeling: An example of flexural peeling of a tension face plate is shown in Fig. 1. The horizontal crack is the flexural peeling crack which always starts at the plate end and propagates inwards until it eventually causes the plate to debond, after which the beam acts as unplated. The mechanism of flexural peeling is very simple and shown in Fig. 2. When a moment (i.e. curvature) is applied to a plated beam, such as the tension face plated beam in a constant moment region in Fig. 1,

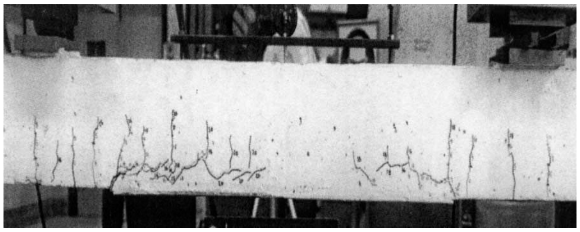

Fig. 1: Premature debonding of a tension face plate.

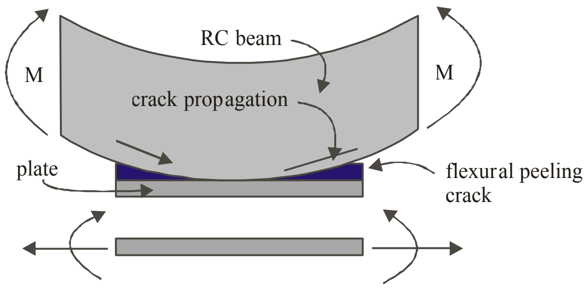

Fig. 2: Flexural peeling mechanism.

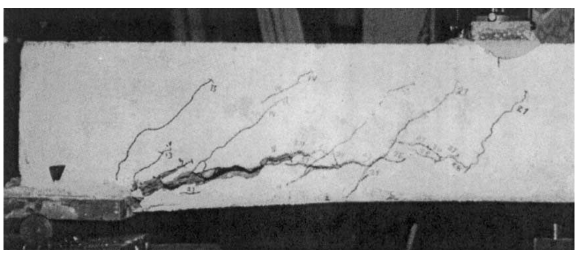

Fig. 3: Shear peeling of tension face plated beam.

then the plate tries to stay straight as shown in Fig. 2 including cracks at the plate end, which propagate inwards. Another way of visualizing this debonding mechanism is to consider the stress resultants that have to be applied to the plate, as shown in the lower diagram in Fig. 2, so that the deformation of the plate would be the same as if it had been attached to the beam. It can be seen that it is necessary to apply an axial force and moment. It is these stress resultants which have to be transferred from the RC beam to the plate that cause debonding.

Shear peeling: An example of shear peeling of a tension face plated beam is shown in Fig. 3. Tests have conclusively shown that shear peeling always occurs after the formation of diagonal shear cracks. The shear peeling mechanism is shown in Fig. 4. The sliding or rotation of the critical diagonal crack causes the debonding crack to start at the base of the diagonal crack and propagate in the direction shown by the arrow. Tests on steel plated beams have conclusively shown that the presence of stirrups does not affect the shear load to cause debonding. This is

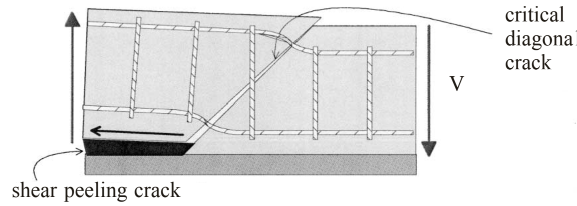

Fig. 4: Shear peeling mechanism.

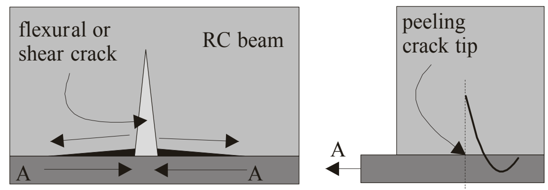

Fig. 5: Axial peeling mechanism.

because the stirrups that cross the diagonal crack as in Fig. 4, have to be stretched before they can contribute to the shear strength of the beam, but as steel plates are fairly rigid they debond as soon as the sliding action occurs. Hence, shear peeling is unlikely to be a major concern when plating slabs where the shear strength is governed by the shear strength of the beam without stirrups V_{uc}. However, shear peeling may severely restrict the plating of beams where the shear load is greater than V_{uc} and where stirrups are supplied to resist the additional shear load V_{us} above V_{uc}.

Axial peeling: Axial peeling occurs when a plate spans across a flexural or shear crack, where it can be seen that wherever a flexural crack touches the plate a debonding crack along the edge of the plate occurs. If debonding did not occur, where the plate crossed the crack, the plate would, in theory, be subjected to an infinite strain, which of course cannot occur. The mechanism by which axial peeling proceeds is shown in Fig. 5.

The infinite strains that have to be accommodated where the plate crosses the crack induce debonding cracks that propagate away from the flexural crack as shown. The axial load A in the plate is now resisted by the uncracked concrete at the end of the peeling crack as well as aggregate interlock or friction across the crack interface.

Debonding due to shear flow: The behaviour of the new composite elements is justifiably expected to be superior to the sum of the behaviour of the two separate elements. For this purpose, the two individual members must be rigidly connected at the interface level, resulting, as closely as possible, in monolithic behaviour. Thus, the interaction at the interface level is the critical parameter in the behaviour of the new composite member. The strength capacity of the composite member is also depend on the interface shear transfer ability. The shear flow in the interface level causes slip action. Failure can occur by interface connection failure, when the magnitude of slip overcomes a critical value.

Preventing debonding: Jones *et al*.[10] stated that applying anchor plates to the plated reinforced concrete beams could provide at least the following three functions,

- To resist the peeling effect
- To prevent debonding and longitudinal plate movement.
- To act as a transition between the plated and unplated sections.

Debonding due to shear flow can be prevented by using shear connector or epoxy resin adhesive. These can be calculated by using conventional shear flow theory.

Conclusion: Strengthening of reinforced concrete beam is one of the important tasks normally associated with on the maintenance of concrete structures. The load carrying capacity of the strengthened beams will increase if monolithic or conjugate action exists between the existing beams and the strengthening materials. The monolithic action will be achieved by using either chemical bonding materials (epoxy resin adhesive etc.) or mechanical shear connectors at the interface between the strengthening materials and the existing beam and with proper end anchorage. For this purpose different types of strengthening materials are available such as sprayed concrete, steel plate, fibre reinforced polymer (FRP) and ferrocement. In general plating methods of steel plate and FRP are more preferable due to several advantages such as easy construction work, minimum change in the overall size of the structure after plate bonding and less disruption to traffic while the strengthening is being carried out. However, premature plate end debonding seems to be the major problems of this plating method which can be prevented by using proper end anchorages.One of the current interests in the field of strengthening is strengthening of reinforced concrete beams for repeated loading condition. This is required for structures such as bridges, offshore structures.

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